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Method and apparatus for interrogation of birefringent FBG sensors**Background**

This invention relates to a practical method for accurate and high-resolution measurements of the orthogonally polarised reflected Bragg wavelengths from fibre Bragg grating (FBG) sensors with birefringence. A fibre Bragg grating (FBG) is a permanent, periodic refractive index modulation in the core of a single-mode optical silica glass fibre over a length of typically 1-100 mm, formed by transversely illuminating the fibre with a periodic interference pattern generated by ultra-violet laser light, e.g. from an Eximer laser, either by using a two-beam interferometer, as disclosed by G. Meltz *et al.* in ["Formation of Bragg gratings in optical fiber by a transverse holographic method," Opt. Lett., Vol. 14, pp. 823-825, 1989,] or by illuminating the fibre through a periodic phase mask, as disclosed by K.O. Hill *et al.* in ["Bragg gratings fabricated in monomode photosensitive optical fiber by UV exposure through a phase-mask," Appl. Phys. Lett., Vol. 62, pp. 1035-1037, 1993.] An FBG reflects light within a narrow bandwidth, centred at the Bragg wavelength, $\lambda_B = 2n_{eff}\Lambda$, where n_{eff} is the effective refractive index seen by the light propagating in the fibre, and Λ is the physical period of the refractive index modulation. Outside the FBG bandwidth light will pass with negligible loss. If the fibre is birefringent the refractive index seen by light propagating in the two orthogonal polarisation eigenstates of the fibre, n_x and n_y , will be different. Consequently, there will be two orthogonally polarised reflected spectra from the FBG with two Bragg wavelengths with a wavelength separation of $\Delta\lambda_B = 2B\Lambda$, where $B = n_x - n_y$ ($n_x > n_y$). Some birefringence can also be UV-induced through the writing of the grating.

It is known that the reflected Bragg wavelength from an FBG will change with any external perturbation which changes the effective refractive index seen by the propagating light and/or the physical grating period (fibre length), such as temperature and strain. By measuring the reflected Bragg wavelength, using for example a broadband light source and a spectrometer, an FBG can be used as a sensor for measuring such external perturbations. The bandwidth of the reflection spectrum from an FBG sensor is typically 0.1-0.3nm (~10-30GHz).

An external perturbation can also change the birefringence in the fibre, and hence change the wavelength separation between the two orthogonally polarised reflection spectra. This can be

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- exploited to make a sensor where the wavelength splitting is a measure of an external perturbation, such as temperature, strain, or pressure, which directly or indirectly induces extra birefringence in the fibre. Such a sensor can also allow simultaneous measurement of two measurands, such as temperature and pressure/strain, by measuring both the wavelength
- 5 splitting and the absolute wavelengths (or average wavelength). Various birefringent FBG sensors are disclosed in [US Patent No. 5,399,854 to Dunphy *et.al.*, US Patents nos. 5,591,965, 5,828,059, 5,869,835, all to Eric Udd, and US Patent no. 5,841,131 to Schroeder and Udd), and in [Sudo, M. *et.al.*, "Simultaneous measurement of temperature and strain using PANDA fiber grating", Proc. 12th International Conf. on Optical Fiber Sensors," p. 170-173, 1997].
- 10 Interrogation of birefringent FBG sensors has been based on using sensors with sufficient birefringence to cause a splitting of the two reflection peaks which can be resolved by the interrogating spectrometer.

- It is known that one or several reflected FBG sensor wavelengths can be measured using a broadband source, for example an edge-light-emitting diode (ELED) or a superfluorescent fibre
- 15 source (SFS), in combination with a tuneable optical filter, for example a piezoelectric transducer (PZT) tuneable fibre Fabry-Perot filter [Kersey, A.D. *et.al.*, "Multiplexed fiber Bragg grating strain-sensor system with a fiber Fabry-Perot wavelength filter", Optics Letters, Vol. 18, pp. 1370-1372, 1993], or alternatively a tuneable laser source [US Patent no. 5,401,956 (Mar. 28, 1995)], provided the source spectrum covers all possible FBG sensor wavelengths.
- 20 To obtain accurate, repeatable wavelength measurements with these techniques one can use a reference scheme based on the use of a fixed Fabry-Perot filter and a reference FBG with separate detector channels [Norwegian patent No 307357]. There are also various other techniques for wavelength interrogation of FBG sensors with broad band sources, such as edge filtering, interferometric detection and direct spectroscopic detection [Kersey, A.D., *et.al.*,
- 25 "Progress towards the development of practical fiber Bragg grating instrumentation systems," Proc. SPIE, Vol. 2839, 1996].

With standard low-birefringent FBG sensors, inherent or induced birefringence can result in measurement errors caused by the corresponding splitting of the orthogonally polarised FBG reflection spectra. Unwanted birefringence can for example be induced when FBG sensors are

30 embedded in a composite structure. Normally, this splitting is smaller than the reflection

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bandwidth of the FBG. In an interrogation system with a partly polarised source such as an ELED or a polarised tuneable laser, and/or polarisation dependent components, the randomly varying birefringence in the lead fibres between the readout instrumentation and the sensors will cause variations in the relative reflected power in each of the two orthogonal FBG spectra, and hence variations/errors in the measured Bragg wavelengths. Polarisation scrambling techniques have been demonstrated which reduces these birefringence induced measurement errors [Ecke, W., *et al.*, "Improvement of the stability of fiber grating interrogation systems using active and passive polarization scrambling devices", Proc. 12th International Conf. on Optical Fiber Sensors," p. 484-487, 1997]. Alternatively, one can use an unpolarised source such as an SFS and a system with no polarisation dependent components. However, if the wavelength splitting due to birefringence in the FBG sensor occasionally becomes large enough to significantly change the spectra shape of the reflected spectrum or cause two resolved separate peaks this can give problems for the readout instrumentation and give erroneous results.

Birefringent FBG based two polarisation fibre laser sensors, as disclosed with a distributed feedback (DFB) fibre laser in the Norwegian patent No. 302441 to J. T. Kringlebotn, are attractive for high resolution measurements of birefringence inducing measurands. The laser light at the two orthogonally polarised eigenstates of the laser are mixed in a detector, generating an electrical beat frequency which is a measure of the birefringence induced in the laser sensor by the measurand.

Objects

The main object of the invention is to provide a method for accurate and high-resolution measurements of the orthogonally polarised maximum and minimum reflected Bragg wavelengths from fibre Bragg grating (FBG) sensors with birefringence, using a Bragg wavelength read-out system based on a broadband source or alternatively a tuneable laser source. The aim is to provide a readout system which can measure birefringence-induced splitting of Bragg wavelengths with high resolution and accuracy (ca. 1pm), independently of the magnitude of the splitting. A splitting larger than the FBG bandwidth will hence not be required.

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A second objective is to provide a means for eliminating errors in FBG sensor measurements caused by the grating birefringence in combination with an interrogation system with a partly or fully polarised source and/or polarisation dependent components, independently of the magnitude of grating birefringence and degree of source polarisation.

- 5 A third objective is to provide a means for eliminating signal fading and optimise the signal amplitude of birefringent FBG based two polarisation fibre laser sensors.

Invention

The object of the invention is achieved with a method having features as stated in the
10 characterising part of Claim 1. Further features are stated in the dependent claims. The main part of the invention comprises the use of an electrically controllable fibre optic polarisation controller in combination with an FBG wavelength readout instrumentation system to measure the wavelength splitting of one or several wavelength multiplexed birefringent FBG sensors. The polarisation controller is either i) operated in a scanning mode to cover a wide range of
15 polarisation states in a certain time period, including the two orthogonal polarisation states corresponding to the minimum and maximum Bragg wavelengths, or ii) operated in a tracking mode with electrical feedback from the receiver of the instrumentation system to change the polarisation state in order to track the minimum and maximum Bragg wavelengths of each FBG sensor. The scanning mode can either use random scanning or a programmed sequential
20 scanning to cover a grid of polarisation states on the Poincaré Sphere. The measured minimum and maximum wavelengths provide a measure of the measurand induced birefringence, independently of the magnitude of this birefringence. The invention can in combination with a wavelength read-out unit with a proper wavelength reference system provide absolute measurements of both orthogonal Bragg wavelengths, which enables simultaneous
25 measurements of two independent measurements, such as temperature and pressure.

The invention can also be used to eliminate errors in FBG sensor measurements caused by the grating birefringence in combination with an interrogation system with a partly or fully polarised source and/or polarisation dependent components, independently of the magnitude of grating birefringence and degree of source polarisation.

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Finally, the method provides a means for eliminating signal fading and optimise the signal amplitude of one or several birefringent FBG based two-polarisation fibre laser sensors.

Examples

- 5 The invention is described with reference to the illustrations, in which

Fig. 1a shows a preferred embodiment of a wavelength measurement device for demultiplexing and demodulation of several birefringent FBG sensor wavelengths based on a polarised wavelength swept narrowband source in combination with an automatic polarisation controller.

- 10 Fig. 1b shows one possible polarised wavelength swept narrowband source, based on a broadband source in combination with a tuneable optical filter and a polariser.

Fig. 2a shows a schematic illustration of the two orthogonally polarised reflection spectra of an FBG.

- Fig. 2b shows the variation in measured Bragg wavelength of a birefringent FBG using a
15 wavelength readout system based on a polarised source in combination with an automatic polarisation controller which is operated in a random scanning mode.

Fig. 3 shows a preferred embodiment of a measurement device for demodulation of a birefringent two-polarisation DFB fibre laser sensor using an automatic polarisation controller to optimise the beat signal between the two orthogonally polarised laser modes.

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- Fig. 1a shows a preferred embodiment of the wavelength measurement arrangement used for measuring the Bragg wavelengths of one or several wavelength multiplexed birefringent FBG sensors, based on a polarised wavelength swept narrowband source in combination with an electrically controllable fibre optic polarisation controller. The source can either be a tuneable,
25 polarised laser or a broadband source in combination with a tuneable optical filter and a polariser, as shown in Fig. 1b. The arrangement includes a reference system based on a fixed Fabry-Perot filter in a separate branch with a separate detector, in combination with a reference FBG. The reference fixed Fabry-Perot filter and the reference FBG should have very low birefringence, with a birefringence induced wavelength splitting of $<1\text{pm}$.

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pump laser (1) is launched through a fibre WDM coupler (2) via an optical fibre to generate lasing in one or several DFB fibre laser sensors (3) (the figure shows only one laser sensor). The generated narrowband laser light at two orthogonal polarisation states with a wavelength splitting $\Delta\lambda$, proportional to the measurand induced birefringence of the laser sensor, is directed through the WDM (2) via an automatic polarisation controller (4) and a linear polariser (5), onto a detector (6) to generate an electrical beat which is directly proportional to the measurand induced birefringence. The automatic, electrically driven polarisation controller (4), is either operated in a scanning mode to cover a wide range of polarisation states in a certain time period, or operated in a tracking mode with electrical feedback from the signal processing unit (7) of the instrumentation system to change the polarisation state, to align the two orthogonal polarisation states at 45° relative to the linear polariser (5) to maximise the electrical beat signal amplitude. It can also be cases where one is interested in minimising the electrical beat signal amplitude to generate single polarised laser light. This can be done with the presented method.

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